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INVESTIGATION OF AIR FLOW NEAR A MACH NUMBER OF ONE, BY THE SCHLIEREN METHOD

BY

DAVID WAYNE WATKINS, JR.

Cambridge, Massachusetts,
June 3, 1946.

Professor George W. Swett,
Secretary of the Faculty,
Massachusetts Institute of Technology,
77 Massachusetts Avenue,
Cambridge, Massachusetts.

Dear Professor Swett:

Herewith I submit my thesis entitled, "Investigation of Air Flow Near a Mach Number of One, by the Schlieren Method" in partial fulfillment of the requirements for the degree of Master of Science in Aeronautical Engineering at the Massachusetts Institute of Technology.

Respectfully,

David W. Watkins Jr.

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David Wayne Watkins, Jr.
Lt. Comdr., U. S. Navy.

Submitted in Partial Fulfillment of the

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from the

Massachusetts Institute of Technology

1946

Signature of Author: David W. Watkins Jr.

Department of Aeronautical Engineering, June 1946.

Signature of Professor in Charge of Research: Joseph H. Keenan

Signature of Chairman of Department Committee on Graduate Students: C. S. Draper

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ACKNOWLEDGMENTS.

It is with pleasure that I acknowledge my indebtedness to Professor J. H. Keenan, who suggested the thesis problem and the possible lines of attack, and helped me constantly through conference on the many difficulties I encountered. Mr. E. P. Neumann also gave freely of his time and offered many valuable suggestions, especially in connection with the investigation of the boundary layer. Mr. A. H. Shapiro suggested an explanation of the multiple shocks observed. Mr. F. Lustwerk explained the use of the Schlieren equipment, and helped with collateral reading. Professor H. E. Edgerton lent his high speed movie equipment, explained its use, and aided me in the development of the film. Mr. Charles Wyckoff gave many days of his time operating the movie equipment. The personnel of the Boston Naval Shipyard permitted free use of their photographic laboratory and helped me with printing the pictures.

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SUMMARY.

The problem investigated was the manner of dissipation of shocks in air flowing through a nozzle. The shocks observed were oblique shocks. They were formed by decreasing the back pressure on the nozzle exit by means of an ejector. The mouth of the nozzle was open to laboratory air. The back pressure was increased after the shocks were formed by closing the valve between the nozzle exit and the ejector, causing dissipation of the shocks. The phenomena were observed by means of a high speed movie camera. The results indicated that the shocks formed dissipated in the throat of the nozzle. They were never observed upstream from the throat.

INTRODUCTION.

In a Schlieren study of two dimensional ejectors, Mr. F. Lustwerk noted the appearance of a sharp fronted disturbance in the subsonic secondary stream under certain conditions. It was desired to know how long the secondary stream could support this disturbance and the manner of its dissipation.

It was decided to simplify the problem by removing the primary stream from the ejector; that is, to investigate the dissipation of a shock in a two dimensional nozzle. This was done to reduce the number of variables involved, so that some results could be obtained in the allotted time.

To attack this problem, it was decided to set up a convergent-divergent nozzle which was supplied by opening the mouth of the nozzle to the atmosphere, to keep entering turbulence as low as possible, and to supply the necessary controlled pressure drop by means of an ejector and suitable valves. Then the phenomena related to the dissipation of the shocks formed in the nozzle could be observed through a Schlieren optical system and recorded on a photographic medium. A few single flash pictures were taken to ascertain that there were dynamic effects to be observed. Then high speed movies were taken of these effects.

APPARATUS.

The major piece of equipment used in this investigation was a double pass Schlieren optical system. Fig. 1 is a sketch of this apparatus, and a more complete description and discussion of it is given in the Appendix.

The nozzle used was a convergent-divergent two dimensional nozzle made of mild steel, with glass end walls. The nozzle was one-half inch wide and for a distance of one-half inch was parallel to the longitudinal axis of the nozzle. The entry to the throat consisted of the arcs of two circles of six inch radii, and extended about three and one-half inches along the longitudinal axis. (See Fig. 2.) The divergent portion of the nozzle consisted of two planes placed at a four degree slope away from the longitudinal axis. The corner between the throat section and the divergent section was carefully blended to destroy the sharp corner. Fig. 3 is a drawing of the frame used to mount the test section. Fig. 4 is a sketch of the nozzle assembly as it was used. The glass walls of the nozzle were made of high grade optical glass, and the surfaces were ground optically flat and parallel.

To take the pictures shown in the results, a standard "Edgerton type", high speed, thirty-five millimeter movie camera was used with an air gap spark substituted for the Edgerton flash tube as a light source. The Appendix fully describes this apparatus and Fig. 5 is a schematic wiring diagram of the light source.

The film used was Eastman Kodak Company's "Super XX", developed for maximum contrast in the same Company's standard developer "D-11" for sixteen minutes. For further discussion of the photography methods see the Appendix.

The required pressure difference across the nozzle was obtained by reducing the downstream pressure from atmosphere by means of an ejector.

The flow of air was from atmosphere, through the test section, suitable piping, a butterfly valve, a silencer, and a globe valve to the secondary stream of the ejector.

In taking a high speed series of pictures, the following procedure was used. The pressure difference across the nozzle was adjusted by use of the globe valve, until a shock was observed in the aperture of the camera. The general illumination in the laboratory was switched off, and the camera was started. The butterfly valve, which was spring loaded to the wide open position, was manually closed. Next, it was allowed to open fully. This valve cycle was repeated two or three times during the exposure of a hundred feet of film. The film speed through the camera averaged about fifty feet per second. This made the time interval between exposures about one five-hundredth of a second. The exposure time of each exposure was about five microseconds.

RESULTS.

The results are presented as pictures in Figs. 6 through 32. They are selected series of enlargements made from one of the hundred foot lengths of exposures made in the high speed camera. The whole length contains about twelve hundred exposures, many of which would be of no interest. In selecting the pictures to be presented, an attempt was made to select those demonstrating most clearly the phenomena occurring in the fewest number of exposures. Since time was an element of interest in the investigation, the continuity of each series was maintained; that is, within each series, the pictures presented follow each other in sequence, with a time interval between pictures of one five-hundredth of a second. The boundary layer group of pictures are an exception to this in that they were of necessity made on another strip of film and were isolated selections and not a continuous series.

Figs. 6 through 13 are one series. This series demonstrates the nature of the multiple shocks at a pressure ratio somewhat below critical, and are from a section of the film in which no change was occurring in the back pressure. They show clearly the oscillations of the shocks occurring in the "steady state" condition.

Figs. 14 through 18 show the manner of dissipation of the shocks with increasing pressure ratio.

Figs. 19 through 27 show the manner of formation of the shock with decreasing pressure ratio.

Figs. 28 through 32 are the pictures of the boundary layer, selected to show variations in pressure ratio from below critical to one.

It should be noted that no attempts have been made to obtain quantitative results because such results, using a double pass Schlieren optical system, are extremely difficult to obtain.

The disturbance which may be noted on one side of the nozzle throat of all pictures was caused by a small nick in the corner of the nozzle half. This nick was about .01 inches deep by .01 inches across and about one-eighth of an inch long.

DISCUSSION OF RESULTS.

As can be seen in Fig. 6, the change from supersonic flow in the throat to subsonic flow downstream of the throat occurred through a multiple shock. Taking Fig. 10 as an example, and considering the occurences in the direction of flow: the velocity increases through the throat section. Just behind the throat, a region of compression occurs which is thicker in the center of the flow area and decreases to a point before reaching the nozzle boundary, thus indicating the presence of a boundary layer. The downstream side of this region is flat. Next downstream is a region of expansion which appears to be a mirror image of the compression region. At the centerline, the expansion region grades into another compression. Away from the centerline and between the first expansion and the following compression, lies a wedge shaped constant flow region. Following the second compression the above described phenomena appear cyclically.

It appears that other photographs contain the same type of compression-expansion waves though not so symmetrically arranged, and the outer ends of the upstream side of the compressions are seldom so clearly bent downstream from the centerline of the nozzle.

Figs. 14 through 18 show the dissipation of these shocks. They move into the throat and weaken in intensity. They were never observed upstream of the throat section.

This would indicate that the subsonic stream will not support this type of shock over any considerable distance, if at all.

Since other shocks have been observed in a subsonic stream, as was mentioned in the Introduction, the question of the mechanism of the shocks observed becomes paramount. Two attacks are possible; one is to start with the hypothesis that the compression shock forms itself in midstream. Then by observing closely Figs. 28 through 32, which are photographs of the boundary layer, slight waves in the boundary layer can be detected. The key to the nature of the shocks lies in the relation of these waves to the shocks. Considering the boundary layer as a region of constant pressure, the reflection of the compression shock is a "Prandtl-Meyer expansion wedge". As has been noted, an expansion exists after the compression shock. Then the next compression-expansion series follows since supersonic flow may exist out of the first expansion. This process is repeated until finally subsonic flow is attained from the last expansion wedge. There is no apparent relation between one shock (compression and expansion) and the cycle following it.

The weakness in this explanation lies in the hypothesized compression shocks which must start in midstream.

If, on the other hand, consideration is first taken of the boundary layer, which is evidently rather thick, then the following explanation may be made. Slight variations in

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the thickness of the boundary layer caused by local oscillations in velocity and pressure such as have been found on investigating the boundary layer of a flat plate (Ref. 3) lead to the conclusion that a convex boundary layer surface may exist. If it is further assumed that the flow in the stream attempts to follow these fluctuations in the boundary layer thickness, then the situation as described in Ref. 4 exists. That is, the flow along a curved boundary is continuous as long as the radii vectors drawn at Machs angles from any point on the boundary do not intersect. When the boundary reaches a sufficient degree of concavity, the radii vectors do intersect and a region of discontinuous flow results. The compression wave thus formed would occur slightly downstream of the concavity in the boundary layer which caused it, thus causing a region of higher pressure at a point where the tendency of the boundary layer is to expand. To equalize the pressure, the boundary layer contracts causing an expansion of the free stream greater than the nozzle walls indicate. The turning of the free stream causes a further depression of the boundary layer which is attempting to expand with the decreasing pressure gradient. As the stream is deflected from the boundary layer a concavity in the boundary layer occurs causing the following compression shock and another cycle of the above mechanism, and so on until subsonic flow results.

In either explanation posed above, each of the multiple shocks would be oblique, not a plane compression shock, and the exit velocity of the stream may be either supersonic or subsonic. In the first explanation posed above, a shock similar to the "hypothesized" shock has been observed in Schlieren pictures of flow around an airfoil taken at the Guggenheim Laboratory at California Institute of Technology. This shock generally slants upstream from the boundary layer and does not lie along a straight line. In the second explanation above, assuming the mean surface of the boundary layer is parallel to the nozzle walls, the shock must slant downstream from the boundary layer, though not necessarily along a straight line. However, if the mean surface of the boundary layer diverges enough from the nozzle walls, then the shock might well slant upstream from the boundary layer. The results of this investigation show no conclusive evidence that the shocks bend in either direction. Also, there is no accurate correlation between any one shock and the boundary layer adjoining it. Hence, no definite conclusion can be reached as to the relation between the waves in the boundary layer and the multiple shocks, except that they both exist at the condition of maximum flow through the nozzle.

The dissipation of these shocks, as may be observed in Figs. 14 through 18, occurs as a weakening of the com-

pression region and a movement upstream into the throat of the nozzle. Apparently the cause of the shocks must move upstream and its intensity must decrease. Since the velocity of the free stream decreases, any cause of the shocks lying in the free stream might be expected to move upstream, but once this motion has started, it would be expected that the motion of the cause of the shocks would not stop at the throat or any other particular point.

On the other hand, if the position of the cause of the shocks is a function of the ratio of the mean boundary layer velocity to the mean free stream velocity, the shocks could conceivably move to a point where this function is again satisfied.

With supersonic flow it is difficult to visualize how a shock caused by free stream disturbances can do anything but move downstream at a velocity equal to the difference between the local sonic velocity and the velocity of the free stream. Figs. 6 through 13 show, however, that a compression wave may be traced from one figure to the next and that the motion of individual shocks may be traced going downstream, then reversing and moving upstream. The rate of change of this motion is about two hundred cycles per second. The region of this oscillation is from the downstream side of the throat section to about one throat diameter downstream of this point.

It is rather easy to visualize this condition when the upstream variation in the thickness of the boundary has a motion of the same frequency. As described in Ref. 4, this oscillation of boundary layer velocity and pressure actually exists on a flat plate in a subsonic stream and hence may be supposed to occur on the surface of the nozzle in a supersonic stream.

It was noted that when the shock was not too far downstream of the throat, but was in existence, a swishing sound could be heard issuing from the nozzle. As the back pressure was decreased and the shock moved further downstream, the sound decreased in frequency and intensity until it could not be heard.

It was further noted that with the maximum pressure difference obtainable across the nozzle the nature of the shock changed slowly with time. When the full pressure drop was attained by opening the valves controlling the flow through the nozzle, the shock appearing on the screen appeared similar to that shown in Figs. 26 and 27. After about forty-five seconds to a minute, this shock would have disappeared and in its place could be seen the multiple shocks similar to Fig. 8 and usually well downstream of the throat. The nature of this slow change was not observed. If the flow was instantaneously interrupted, the single shock of Fig. 27 would again appear.

Professor Keenan has suggested that this may be a temperature effect. The stream being cooler than the surroundings would in time cool the walls of the nozzle and the stream itself would increase in velocity due to the heat absorbed by the stream. As the walls of the nozzle cooled, less heat would be transmitted to the stream, thus decreasing the velocity, and hence the strength of the shock, permitting the multiple shocks to form.

As can be clearly seen in Figs. 25, 26 and 27, a condensation shock was observed. This shock was annoying in that it blanked out some pictures that might otherwise have been of interest. However, its position in relation to the throat remained fairly constant and was generally downstream of the multiple oblique shocks when the pressure ratio across the nozzle was near critical. It is mentioned by way of explanation of the darkened region towards the nozzle exit. It is not felt that this condensation shock had any marked effects on the results. A more complete discussion of condensation shocks may be found in Ref. 7.

The results presented are far from conclusive as to the manner of dissipation of the shocks, as to the nature of the shocks themselves, and as to the relation between the boundary layer and the shocks. It would have been interesting, had time permitted, to find the relation between the boundary layer and the shocks. This could have been

done by taking a run similar to those made with an angle of forty-five degrees between the nozzle axis and the Schlieren knife edge. Correlation of such a set of pictures with those obtained could have been much more informative than the results obtained.

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CONCLUSIONS.

1. The oblique shock observed in this investigation dissipates very quickly or never exists in a subsonic stream.

2. The results indicate that there is a close correlation between the boundary layer and the oblique shocks existing.

3. The noise issuing from the mouth of the nozzle, at pressure ratios slightly below critical, is caused by oscillation of the shock in "steady state".

4. The condensation shock presents no problem in this type of investigation since it occurs downstream of the effects observed.

5. Two distinct types of dynamic change occur under the conditions investigated; namely, a high speed oscillation of the multiple shocks, and a relatively slow change from a plane compression shock to the multiple shocks. Both effects occur with no change in the pressure ratio across the nozzle.

RECOMMENTATIONS.

A quantitative Schlieren investigation of the relation between the boundary layer and the shocks in a supersonic stream might lend much light on the formation and dissipation shocks.

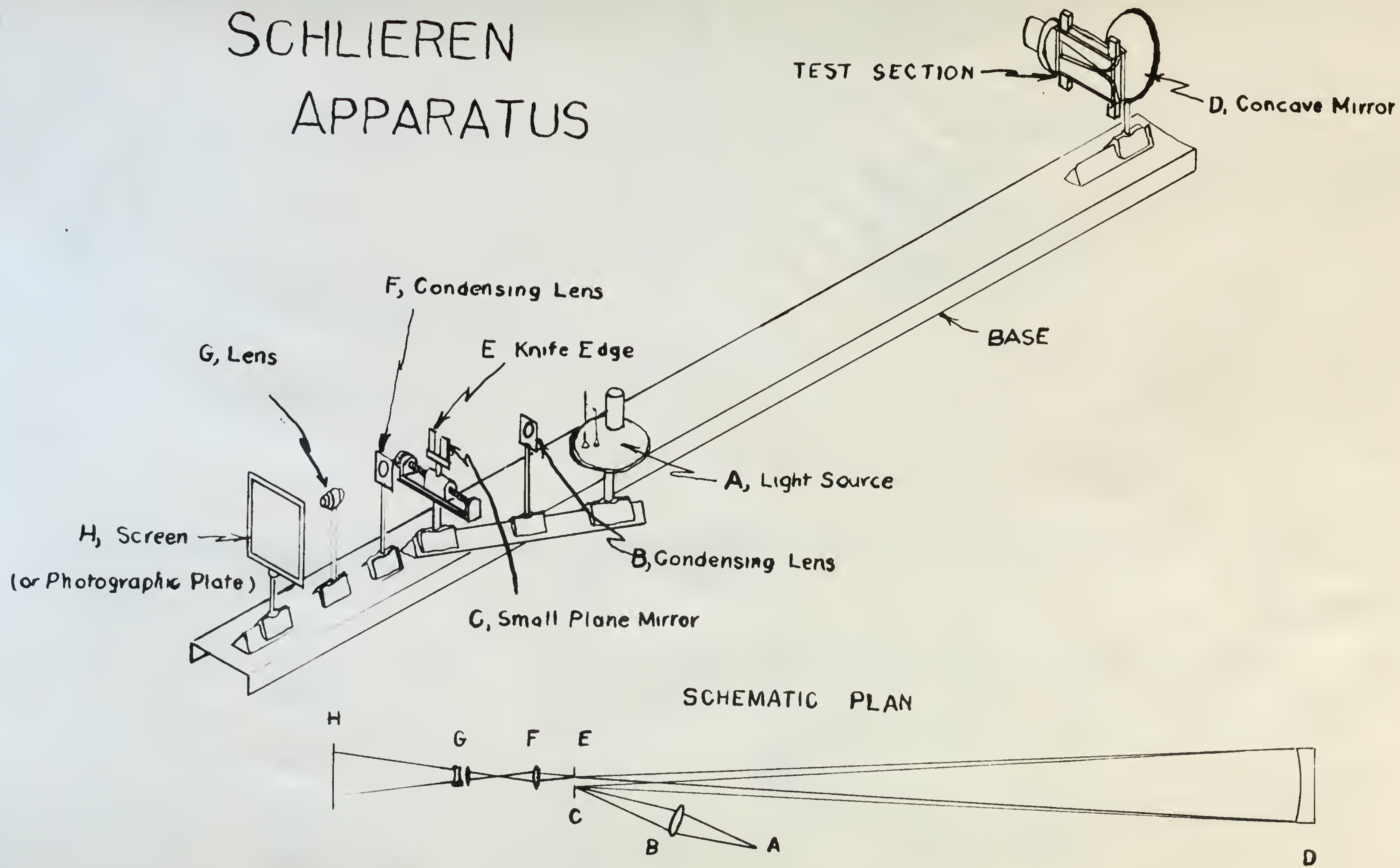

SCHLIEREN
APPARATUS
TEST SECTION
D, Concave Mirror
BASE
F, Condensing Lens
E Knife Edge
G, Lens
A, Light Source
H, Screen
(or Photographic Plate)
B, Condensing Lens
C, Small Plane Mirror
SCHEMATIC PLAN
H
G
F
E
C
B
A
D

Fig. 1

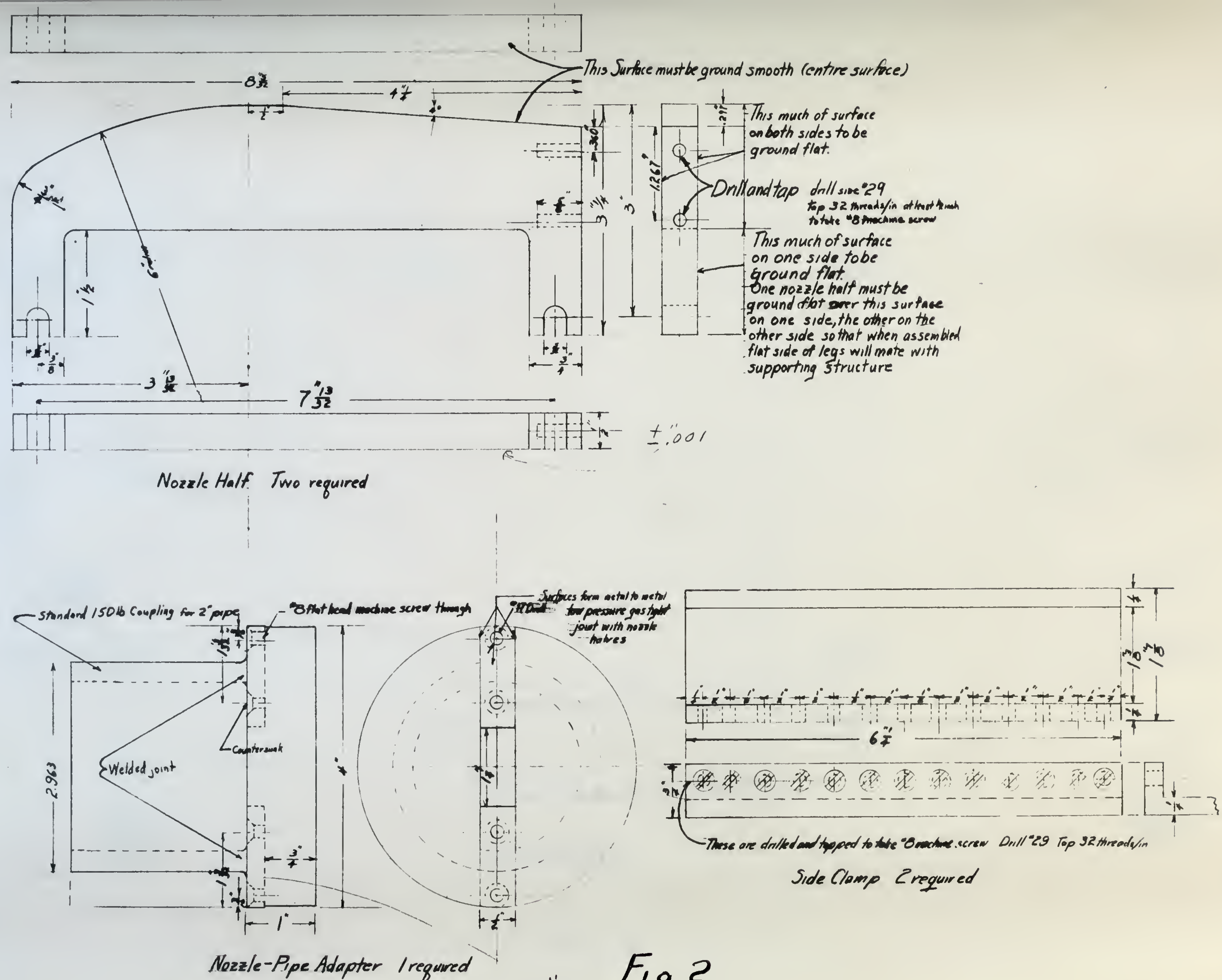
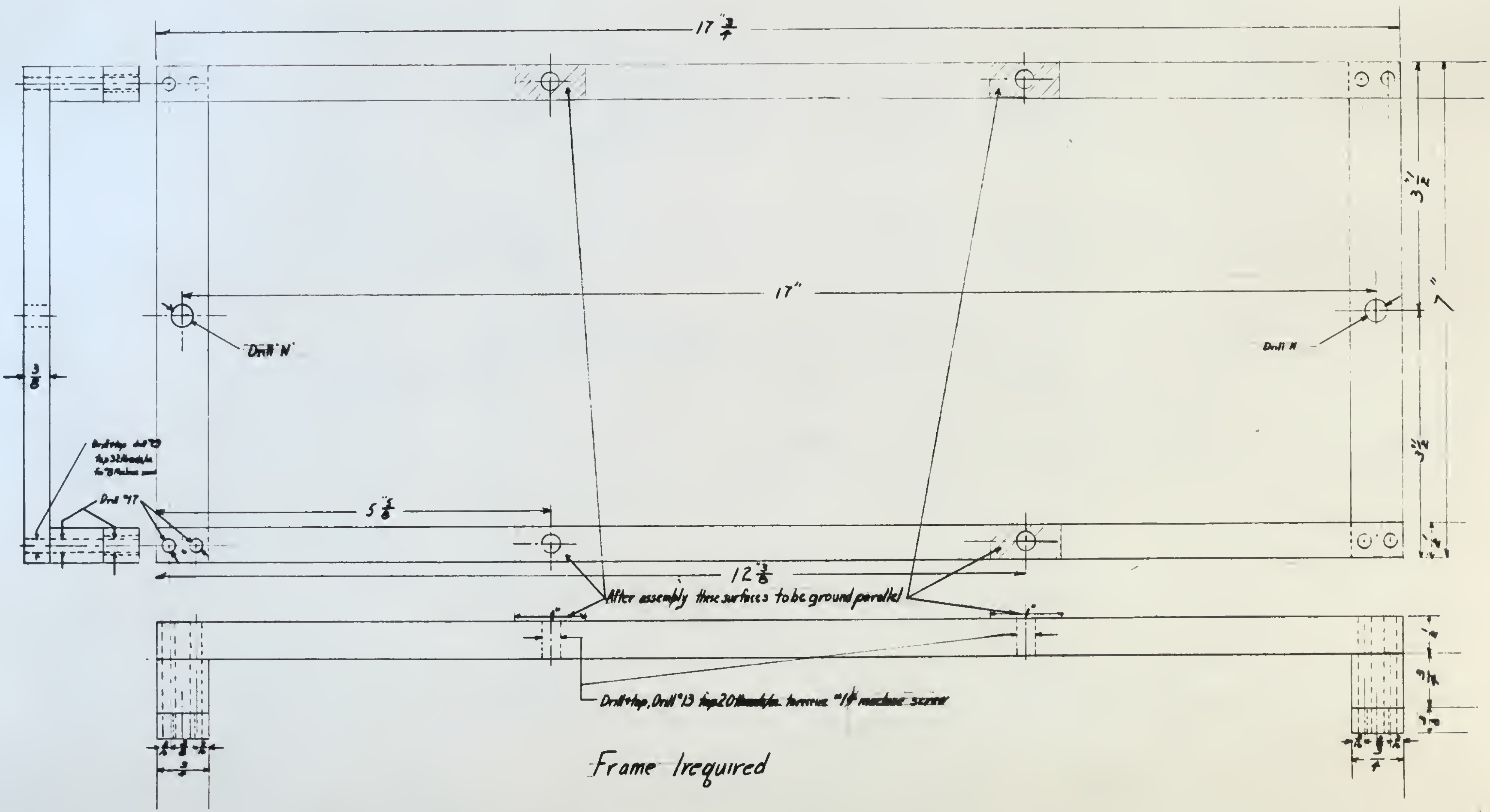

This Surface must be ground smooth (entire surface)
This much of surface on both sides to be ground flat.
Drill and tap drill size #29 Tap 32 threads/in at least ¼ inch to take #8 machine screw
This much of surface on one side to be ground flat.
One nozzle half must be ground flat over this surface on one side, the other on the other side so that when assembled flat side of legs will mate with supporting structure
Nozzle Half Two required
±.001
Standard 150lb Coupling for 2" pipe
#8 flat head machine screw through
Surfaces form metal to metal low pressure gas tight joint with nozzle halves
Countersunk
Welded joint
2.963
Nozzle-Pipe Adapter 1 required
±.001
These are drilled and tapped to take #8 machine screw Drill #29 Tap 32 threads/in
Side Clamp 2 required

Fig. 2



Frame 1 required

Fig. 3

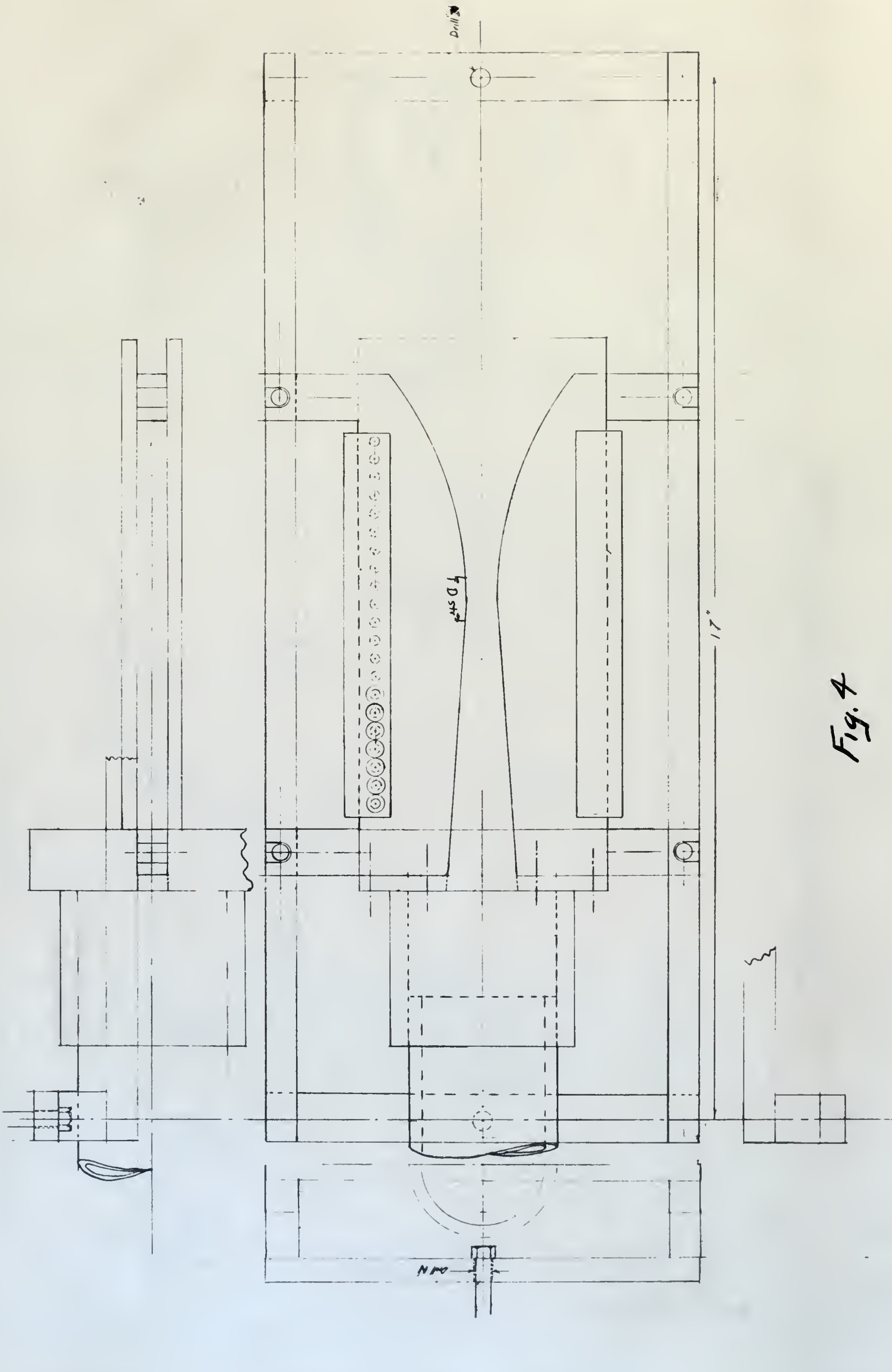
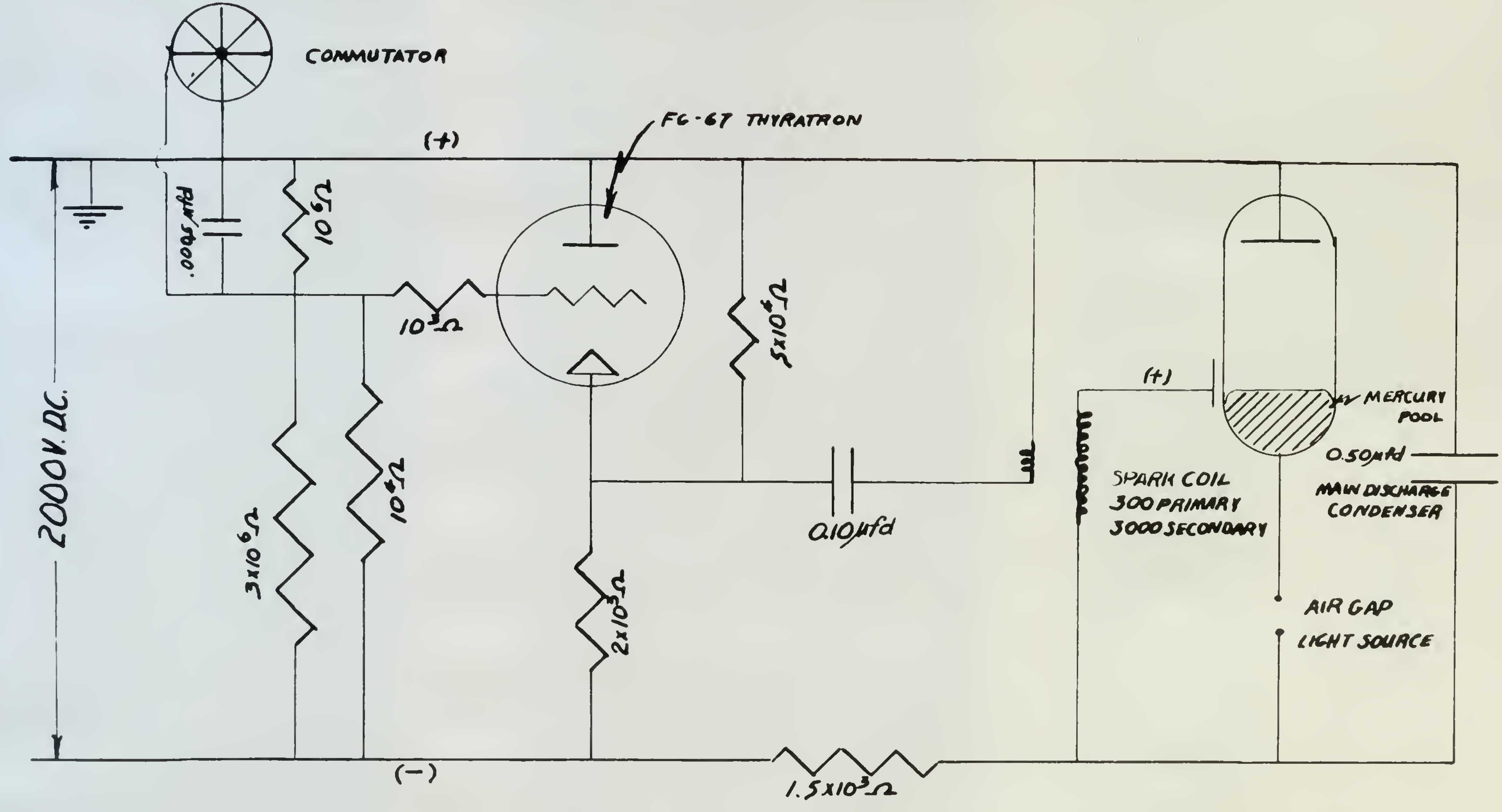


Fig. 4



Schematic Wiring Diagram of Light Source

Fig. 5

FIGS. 6 to 14.

SERIES 1.

TAKEN MAY 9, 1946, AT 3 P.M., AT M.I.T.
PRESSURE RATIO, NOZZLE EXIT TO ENTRANCE, CONSTANT
ENTRANCE PRESSURE, ATMOSPHERIC
TIME INTERVAL BETWEEN PICTURES, ONE FIVE HUNDREDTH SECONDS
EXPOSURE TIME, FIVE MICROSECONDS

FIG. 6.

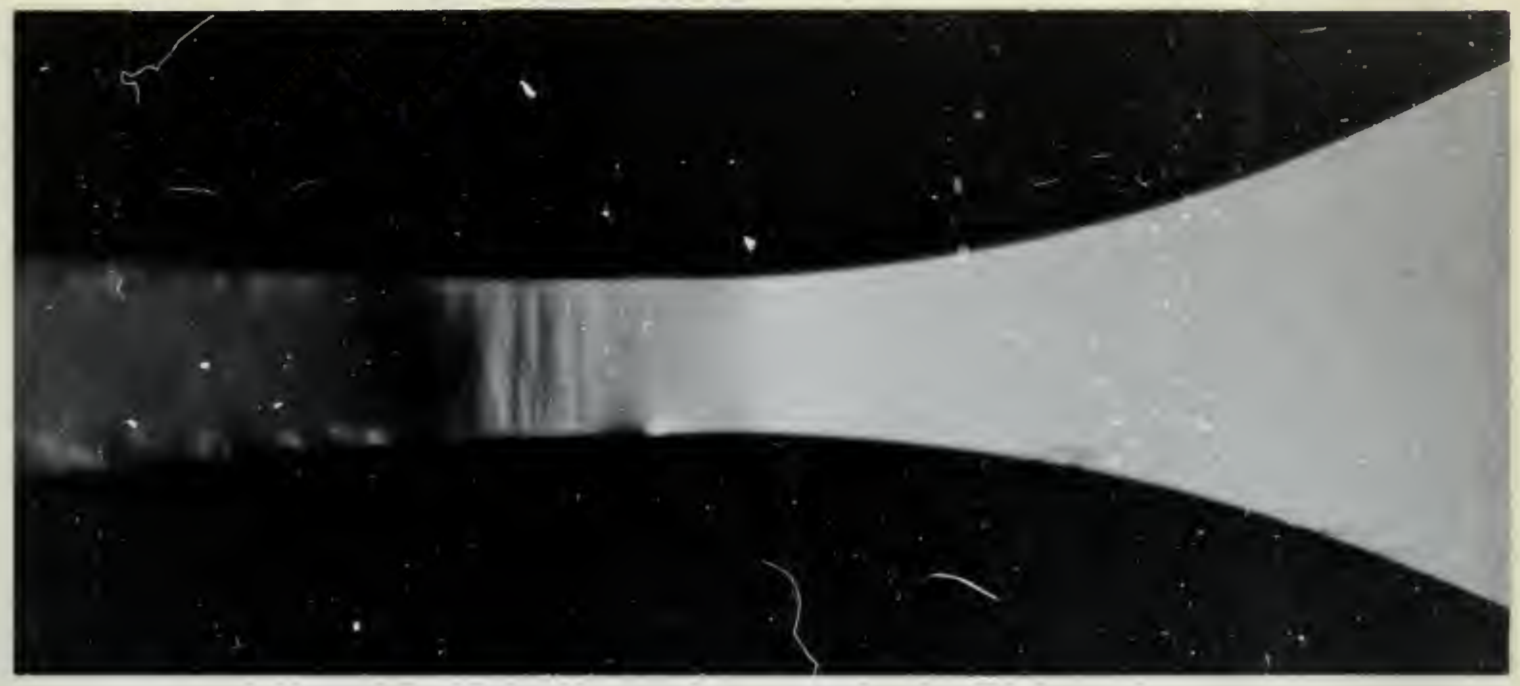


FIG. 7.

FIG. 8.

FIG. 9.

FIG. 10.

FIG. 11.

FIG. 12.

FIG. 13.

FIGS. 14 to 19.

SERIES 2.

TAKEN MAY 9, 1946, AT 3 P.M., AT M.I.T.
PRESSURE RATIO, NOZZLE EXIT TO ENTRANCE, INCREASING
ENTRANCE PRESSURE, ATMOSPHERIC
TIME INTERVAL BETWEEN PICTURES, ONE FIVE HUNDREDTH SECONDS
EXPOSURE TIME, FIVE MICROSECONDS

FIG. 14.

FIG. 15.

FIG. 16.

FIG. 17.

FIG. 18.

FIG. 19.

FIGS. 19 to 28.

SERIES 3.

TAKEN MAY 9, 1946, AT 3 P.M., AT M.I.T.
PRESSURE RATIO, NOZZLE EXIT TO ENTRANCE, DECREASING
ENTRANCE PRESSURE, ATMOSPHERIC
TIME INTERVAL BETWEEN PICTURES, ONE FIVE HUNDREDTH SECONDS
EXPOSURE TIME, FIVE MICROSECONDS

FIG. 20.

FIG. 21.

FIG. 22.

FIG. 23.

FIG. 24.

FIG. 25.

FIG. 26.

FIG. 27.

FIGS. 28 THROUGH 32.

TAKEN MAY 12, 1946, AT 10 A.M., AT M.I.T.
PRESSURE RATIO, NOZZLE EXIT TO ENTRANCE, INCREASING
ENTRANCE PRESSURE, ATMOSPHERIC
EXPOSURE TIME, FIVE MICROSECONDS

Note: Pictures are not separated by constant time interval but are selected to show typical structures found.

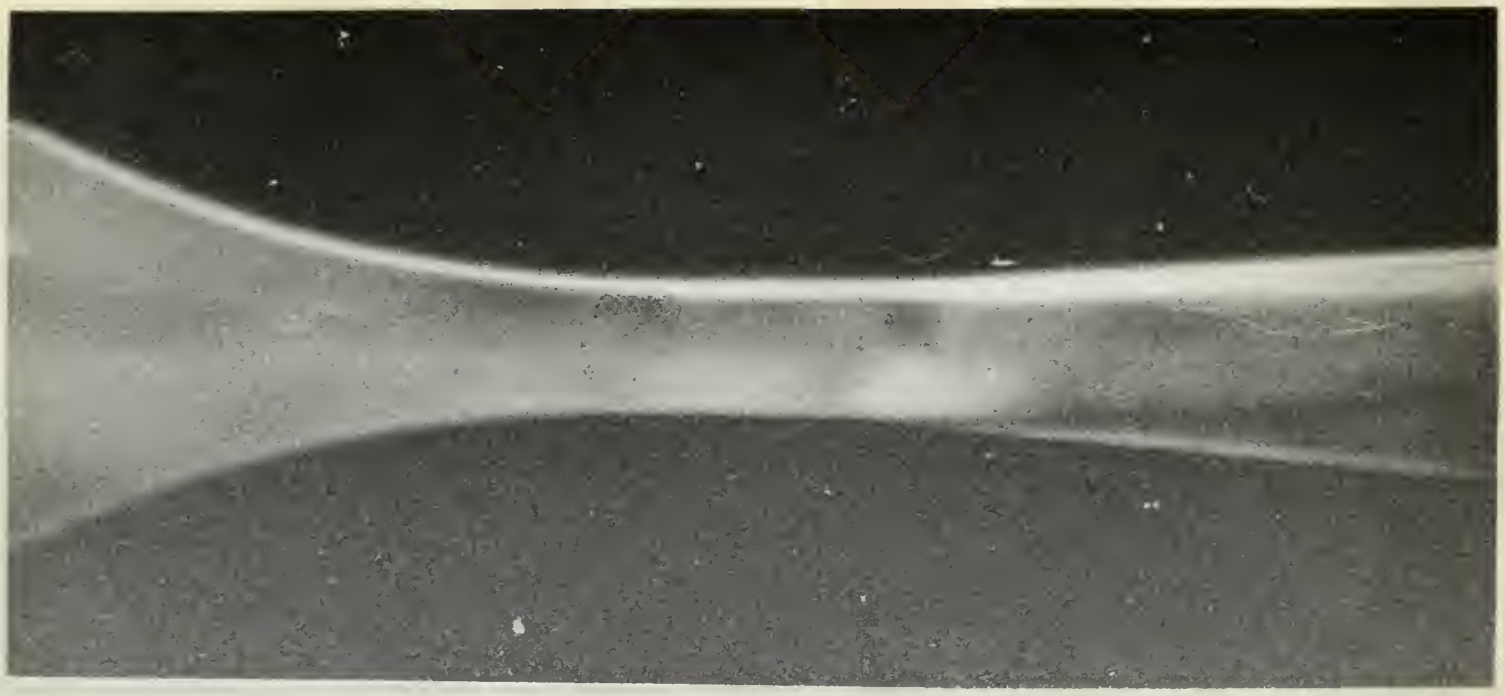


FIG. 28.

FIG. 29.

FIG. 30.

FIG. 31.

FIG. 32

APPENDIX I.

DETAILED DESCRIPTION AND DISCUSSION OF APPARATUS.

THE SCHLIEREN EQUIPMENT

The Schlieren optical method was used to observe the phenomena investigated. The system used is sketched in Fig. 1. It consists essentially of a light source, a small plane mirror, a spherical concave mirror with a twenty-four foot focal length, a knife edge, a screen of ground glass, or photographic film, a system of corrected convex lenses, and the model to be observed.

Referring to Fig. 1, light is collected from the source "A", by the condensing lens "B", and focused on the small plane mirror "C". The point of focus is a point on the side of the plane mirror nearest the optical axis of the bench. A portion of the image of the source is allowed to pass between the mirror and the optical axis. This insures a sharp edge on the image cast back to the knife edge and permits accurate sensitivity adjustments. The light from the plane mirror is then cast through the test section on to the concave mirror "D". Thence the light is reflected back through the test section to the knife edge "E".

The knife edge is in the same plane as the plane mirror. This plane is located at one half the focal length of the mirror away from it, as measured along the optical axis. The

knife edge is parallel to the edge of the mirror nearest the optical axis, so that light passing the knife edge appears as a sharply defined rectangular slit. The condensing lens "F" collects the light and the lens "G" focuses the light so that the test section is defined on the screen.

A decreasing density gradient toward the knife-edge side of the test section (downstream) causes a deflection of the rays passing through the test section away from the knife edge. An increasing pressure gradient in this direction refracts the light toward the knife edge. Thus, a decreasing density gradient in the direction of flow appears as a lighter region and an increasing one appears as a dark region.

A rotating table was used to mount the light source, so that the apparatus would be lined up and adjusted with a steady source; then pictures could be taken with the flash source by merely rotating the table.

The sensitivity is adjusted by moving the knife edge into or out of the beam of light reflected by the concave mirror, by means of a micrometer screw. Moving the knife edge into the beam increases the sensitivity. That is, smaller refractions of the light are blacked out on the viewing screen by the knife edge.

A complete discussion of the adjustments to the apparatus may be found in references (1) or (2).

THE GLASS NOZZLE WALLS

The glass used on the sides of the nozzle had a large effect on the results obtained. First tried, was selected plate glass. This glass was high quality plate glass selected by means of an interferometer for flatness and parallelism of the planes. Selected points in each piece used were examined and at no place was a curvature of greater than thirty seconds of arc observed. However, when placed on the test section and observed through the apparatus, the effects of the glass were smaller but of the same order of magnitude as the compression shock which was under investigation. See Fig. A, Appendix I. Therefore, it was necessary to obtain two optically flat pieces of glass from which no glass effects could be observed through this apparatus. See Fig. 18.

Clamping stresses were avoided by holding the glass in place with cellulose tape. Pressure stresses were small because pressure differences were small, of the order of seven pounds per square inch, and the areas affected were small. The thickness of the glass used to obtain the final results totaled one inch, that is, each piece was one-half inch thick.

THE HIGH SPEED MOVIE CAMERA

To obtain a series of pictures with a short time interval between pictures, a thirty-five millimeter, high speed

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camera was used. The camera consisted of two reels, one for unexposed film, and the other for winding the exposed film, and a sprocket guide wheel, all encased in a light tight box fitted with an exposure aperture. A motor drove the exposed film reel, and the sprocket wheel, turned by tension in the film from the exposed film reel, turned a comutator which actuated the light source. Frames were separated by the flashing light source. The camera and light source were capable of taking pictures at any rate of speed up to twelve hundred frames per second, the speed being controlled by a governor on the driving motor. Timing of the speed was effected by a sixty cycles per second spark at the edge of the film, leaving a blackened area on the edge of the film for each sixtieth of a second of time elapsed.

LIGHT SOURCES

The steady light source consisted of a filament electric lamp.

Several types of flashing sources were used. For the trial single pictures an "Edgerton Flash Tube" was used. This consists of a spark gap in an inert gas. The spark is corded, that is, it is made to pass through a glass tube of about one eighth inch inside diameter. The spark was about one and one-half inches long. (Ref. (2)).

For the high speed series of pictures the same type of tube was tried and found unsuccessful because the spark was

not corded into a narrow enough region. This motion of the spark caused the light to the plane mirror at times to be all on the mirror so that no definition of the edge of the mirror could be detected at the knife edge, hence losing control of the sensitivity adjustment, and at times to be completely off the plane mirror so that no light passed through the remainder of the system.

In an effort to reduce the wandering of the spark an air spark gap was tried, with no attempt made to cord the spark, but wandering of the spark materially reduced by reducing the length of the air gap to about one-quarter of an inch. This scheme was satisfactory but not excellent, since some variation in the density of the frames could be observed.

The mechanism for producing the spark is sketched diagrammatically in Fig. 5. An impulse from the commutator permitted the thyratron to pass current which in turn allowed the 0.10 microfarad condenser to discharge. This caused current to commence flowing in the primary of the spark coil which induced a voltage in the secondary. This voltage in the secondary was enough to "fire" the mercury tube and cause a breakdown across the air gap. Once the mercury tube commenced to pass electrons, the main discharge condenser, discharged across the air gap and through the mercury tube. The 1500 ohm resistor prevented firing of

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the air gap once the main discharge condenser had discharged, but permitted this condenser to build up in voltage when no current was flowing through the air gap circuit. The rectifying nature of the mercury tube prevented a secondary spark from forming due to any inductance that probably existed in the actual main discharge circuit.

PHOTOGRAPHIC TECHNIQUE

It was found that the efficiency of the spark was materially reduced as to its effect on photographic plate when the spark was allowed to discharge through air rather than through an inert gas. Hence, in order to keep the exposure time short, it was found necessary to use the fastest obtainable movie film. It was not considered expedient to hypersensitize slower film due to the uncertainties involved, and the possible striations in the photographic film speed. The film used was Eastman Kodak Company's "Super XX".

In the development of the film it was found that maximum contrast could be obtained by chemically fogging the film very slightly. This merely ensured full development of all light struck portions of the exposed film. In order to do this the commercial developer "D-11" produced by Eastman Kodak Company was used and a developing time of sixteen minutes was used. The temperature of the developer was maintained as nearly at 68 degrees F. as possible to prevent excessive grain size in the negative.

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HEAT STRIATIONS

Heated wires were placed across the nozzle entrance parallel to the optical axis, in an effort to follow streamlines in the flow through the nozzle. However, these were found to disrupt the flow considerably and at maximum flow it was not feasible to heat the wires enough to follow the streamlines through the throat. It was feared that too much heat applied locally near the glass walls of the nozzle might break them. In obtaining the final results this scheme was abandoned.

ADJUSTMENTS AFFECTING RESULTS

It was found that relatively small movements of the light source in a lateral direction caused shifts in the image which varied the sensitivity from "dark field" to no sensitivity at all. Movements of the order of a sixteenth of an inch from the mean were all that were necessary to provide this change in the position of the image relative to the knife edge. It was further found that motion of the light source of the same order of magnitude along the optical axis gave the same effect on the viewing screen due to motion of the focal point of the concave mirror relative to the knife edge.

It was found that when the glass walls of the test section were perpendicular to the optical axis reflections from the surfaces of the glass threw stray light into the screen that was not tolerable. Hence, all pictures are taken with

an angle of about four degrees between the optical axis and a perpendicular to the plane of the glass walls of the test section.

The interval between frames was taken at about one five-hundredth of a second because the spark source was more dependable at this slow speed, and because some experimental shots taken at higher speeds up to eleven hundred frames per second indicated that local movements of the shock occurred at much higher speeds. The camera would only handle one hundred foot lengths of film and at higher speeds, after allowing for the camera to steady on the set speed, too short a total time interval was left for the manual operation of the butterfly valve. It was thought that the sudden closure of the valve by automatic means might inject air inertia problems into an already complicated one. Therefore, the high speed series of pictures taken are not continuous; that is, when shown through a moving picture camera they do not show the movement of the multiple shocks relative to each other in a smooth continuous motion.

The negatives of the results have not been cut, so that each rum remains intact as it was made. These negatives are presented with the original copy of this thesis to M.I.T.

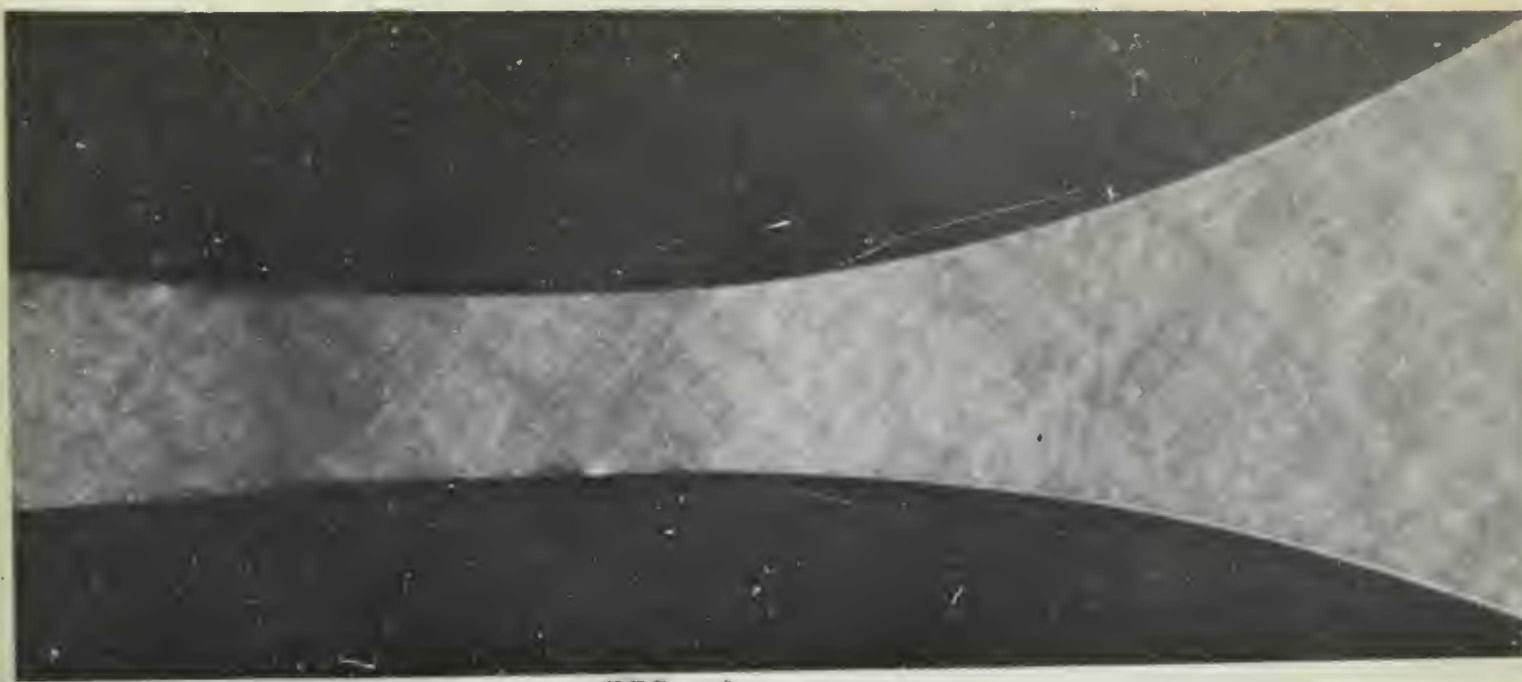

FIG. A.

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